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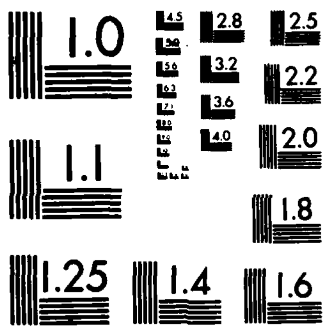

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Analytical work devoted to the global acoustics has been concerned with both linear and nonlinear behavior. Good agreement has been found between calculations of the mode shapes and data taken at the Naval Weapons Center. Numerical calculations are in progress to provide representation of the nonlinear unsteady behavior of a normal shock wave in an inlet diffuser, including viscous effects.

Experimental investigations of combustion have been carried out with pressure, spectral line intensity and flow visualization techniques in a burner equipped with a bluff body flameholder. When the combustion is stable, the flow in the flameholder shear layers has many of the characteristics of isothermal shear layers. When unstable combustion occurs, the shear layers are characterized by large vortices which are shed from the flame holder lip. The self excited oscillations appear to result from a coupling between the vortex production mechanism and nonsteady heat addition in the vortex. Both steady and nonsteady processes are being studied. (over)

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Calculations of the combustion augmentation associated with the interaction of a burning vortex with a wall, show a well-defined combustion rise but somewhat less marked than was expected on the basis of experimental observations.

A

I. RESEARCH OBJECTIVES

AFOSR-TR- 86-1061

This report covers the fifth year of a program concerned with the mechanisms for low frequency pressure oscillations in ramjet engines. Both analytical and experimental work are included. The analysis covers both detailed examination of specific mechanisms and the acoustical framework within which the relative influences of various mechanisms may be assessed. The experimental work is initially being performed in a small scale laboratory dump combustor.

A. Analytical Work

1. Modelling the Steady Flow Field in a Dump Combustor

As part of the basis for carrying out analysis of the unsteady motions, it is necessary to have a model of the steady flow field. The purposes of the present program, items 2 and 3 below, are adequately served by a relatively crude approximation to the actual field. We assume that combustion occurs in a flame sheet anchored at the dump plane. Ignition of the incoming flow is sustained by hot gases supplied from the recirculation zone which is separated from the main part of the chamber by a shear layer. The shear layer is approximated as an infinitesimally thin discontinuity of velocity. To the greatest extent possible, integral methods are used to formulate approximate solutions for the various regions of the chamber. Errors in the representation of the steady flow field can be tolerated because the results will appear only as parts of

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integrals in the analysis of the acoustic field. Refinements in the representation will be incorporated on the basis of comparison with experimental data. The main improvements required have been related to a more realistic representation of the unsteady energy release in the combustion processes.

2. Analysis of the Linear Acoustic Field

The description of the acoustic field will be constructed in the manner used to analyze corresponding problems in liquid and solid rockets. Modifications are required to accommodate the strong gradients of the average temperature and velocity fields. Moreover, account must be taken of the inlet shock system and the high speed flow in the inlet. Early emphasis has been placed on one-dimensional approximations to the acoustics field: the wave fronts are then planar. In later stages, two-dimensional analyses will be carried out for closer representation of the motions in operation combustors.

3. Analysis of Nonlinear Acoustics

Approximate techniques, developed and used for studying pressure oscillations in solid propellant rockets, will be used to analyze nonlinear behavior in ramjet engines. The ultimate purpose is to understand the processes responsible for limiting the amplitudes of steady oscillations. The nonlinear behavior of a shock wave in a diffuser will be treated numerically to provide the upstream boundary condition for the acoustics field. Approximations to viscous effects will be included.

4. Comparison With Data

Results of the analyses will be used to correlate and interpret data. In addition to data acquired in the present program, we are supplied with observations and measurements taken with a laboratory combustor operated at the Naval Weapons Center, China Lake.

5. Analysis of Non-steady Combustion Fields

The work concerning the behavior of flames and combustion in vortex structures has revealed a surprising order in the overall reactant consumption rate, in contrast with the general complexity of the gas-dynamic field. Most of our detailed results deal with initially un-mixed gaseous reactants and treat the field of a single vortex rather than a group of interacting vortices. The novel feature of the vortex combustion of pre-mixed reactants lies in the somewhat different behavior of pre-mixed flames under conditions of straining and extension. The effects of finite chemistry, particularly as to extinction under conditions of straining, are similar for both situations.

Two specific mechanisms for self-excited combustion oscillations were proposed at the initiation of this grant. The first was associated with vortex shedding from flame holding devices, the vortex shedding being forced by the acoustic oscillations that were, in turn, excited by the delayed combustion of these vortex structures. The frequencies of these oscillations are in the kilohertz range and involve, in an essential way, the interaction between flame chemistry and flame straining rate. The second has to do principally with the Kelvin-Helmholtz instability of vortex sheets shed from curved flame fronts. This unstable flow distorts the flame front further, thereby augmenting the strength of the vortex sheet and feeding the Kelvin-Helmholtz instability. Analytical studies related to each of these mechanisms will be pursued throughout the next year of the grant.

Recent experiments have indicated, contrary to our initial expectations, that the time delay associated with finite reaction rate may indeed be a factor of interest in some of the frequencies that are being encountered. Our analytical study of instability mechanisms will be altered to account for finite chemistry.

B. Experimental

The general objective of the experimental program is to obtain a body of information which can be used to develop rational models for several types of combustion instability. The models must be sufficiently accurate and detailed so that they can be used to predict when these instabilities will be present in a given combustion system. The experimental system used in this study is a simple model of a dump burner configuration such as that which would be used in a ramjet system, but the results obtained with this experimental system will be generally applicable to any system utilizing a bluff body type of flame holder.

The experiments are being carried out in a premixed stream of fuel and air, and methane is the primary fuel. A small blowdown facility is being used and the instrumentation includes time and space resolved measurements of the pressure and the intensity of radiation from the burner. Flow visualization techniques include the use of shadowgraph photographs with both microsecond duration, spark light source and high speed movies. Simultaneous measurements of light intensities and pressure fluctuations at a number of positions in the duct give the good qualitative picture of the interaction between pressure and heat release fluctuations which is required for the development of physical models for the instability process.

Changes in the geometry and acoustic damping of various parts of the supply system allow us to determine the response of the combustion process to pressure perturbations with a wide range of frequencies and amplitudes. The use of mixtures of various proportions of methane and hydrogen as fuel make possible the exploration of the dependence of the instability process on the chemical reaction rates. Because the heating value of these gases are almost equal, changing the mixture ratio of fuels does not affect the overall heat release when we compare different fuel compositions but keeps the fraction of the stoichiometric fuel-air mixture ratio fixed. However, the chemical reaction time for hydrogen is much shorter and hence the influence of reaction rates on instability phenomena can be examined cleanly by changing the mixture ratio of hydrogen and methane.

Data are acquired at a rate of 5 kHz per channel and spectral analyses of several types are being carried out.

Emphasis is being placed on the study of the generation and subsequent growth of large vortices which are associated with one form of combustion instability.

II. STATUS OF RESEARCH

A. Analytical Work

1. Modelling the Steady Flow Field in a Dump Combustor

The modelling of the steady flow field for axial dump combustors was completed during the second year with some refinements made during the third year; numerical results have been obtained. It is convenient to divide a complete engine into three parts: the inlet duct, the main combustion region in the combustor, and the zone within the combustor but downstream of the combustion zone. With the assumption that both the flame sheet and the shear layer are adequately represented as infinitesimally thin sheets, the combustion zone comprises three regions: the unburnt flow of reactants upstream of the flame, the downstream flow of combustion products, and the recirculation zone also containing products of combustion. The treatment of the recirculation zone was changed during the third year. It is now based on a recent method using conformal transformations worked out by a graduate student in the Applied Mathematics Department at Caltech. A brief description of the method appears in the thesis by Yang.

An integral method has been used to treat the flows upstream and downstream of the flame sheet. The solutions are matched at the flame sheet. As an approximation, the vorticity is assumed uniform within the recirculation zone. Solution for the velocity field is then obtained numerically, and matched to the flow of combustion products at the shear layer.

The results have shown reasonable behavior for the shape of the flame sheet and of the surface representing the shear layer. The solutions appear to be relatively insensitive to the value assumed for the vorticity in the recirculation zone.

Some work has been started on flows with a laminar flame normal to the flow in a duct. This is obviously unrealistic for practical problems but serves as a simple first step in a study of the influences of entropy waves in combustors.

2. Analysis of the Linear Acoustic Field

A computer program has been written and numerical results have been obtained for the linear acoustic field in an entire engine. The boundary condition at the inlet is given by a previous analysis of the normal shock, completed in the first year of this program; or by using the nonlinear numerical analysis completed later. Results for the amplitude and phase distributions for the pressure field in the inlet agree satisfactorily with measurements taken at the Naval Weapons Center. One example of the amplitude distribution in the combustion chamber also shows fairly good agreement with observations. Further comparisons with data will be done as more results are obtained at the Naval Weapons Center and in the present program at Caltech.

The linear analysis worked out here is also being used very successfully as an aid to interpreting behavior observed in the experimental portion of the present program. Those results are discussed below.

The early representations we used for unsteady combustion processes is incomplete. As a result, all modes of oscillation were predicted to be stable. Initial steps have been taken to improve this part of the analysis with some more realistic results appearing in Yang's thesis. Much remains to be done, including the incorporation of vortex combustion and entropy waves.

3. Analysis of Nonlinear Acoustics

Some of the effort during the first two years of this program was devoted to approximate analysis of nonlinear behavior. Primarily, we were concerned with problems relating to the existence and stability of limit cycles. Some of the results obtained were reported at the 1983 and 1984 AIAA Aerospace Sciences Meetings. An extended paper will appear in Vol. 66 of Combustion Science and Technology. Support of that work has been transferred to another program.

As a separate effort, we carried out a numerical analysis of the behavior of a normal shock wave in a duct. The eventual purpose is to represent the unsteady behavior of a shock, including the effects of viscous boundary layers and shock/boundary layer interaction. Good results were obtained for the steady and unsteady behavior of a shock wave with no viscous effects and for a steady shock wave including viscous effects with attached boundary layers. The analysis has been extended to provide detailed and informative results for the pressure and temperature (entropy) waves in the diffusers. Some influences of fuel injection have also been examined. This work will appear in a paper to be published in the AIAA Journal of Propulsion and Power.

4. Combustion with Multiple Vortices

The studies of combustion in multiple vortices was intended to help understand the non-steady combustion processes where the field contains more than a single vortex, as well as the very important issue of combustion in vortices that interact with a wall. The wall interaction has appeared, from the experiments, to be of considerable importance. The results, to date, have not shown the striking increase in combustion intensity which was anticipated from the vortex interaction. It was expected that, as a vortex approached the wall and interacted with its image, the combustion intensity would rise rapidly, providing the combustion pulse required to induce the formation of the next vortex. This does happen to some extent but less vigorously than was expected.

These interaction problems are being studied further and, in some of the studies, finite chemical rates will be included also.

One of the novel phenomena that arises in unsteady combustion problems is the interaction of acoustic waves or shock waves with the non-uniform density fields caused by flames. When a diffusion flame, for example, encounters a pressure gradient parallel to the flame, the gas responds with an acceleration that is inversely proportional to the density of the gas. As a consequence, the hotter, less dense inner portion of the flame moves at a much higher velocity than the cooler gas and a strong shear layer is formed. Because this can lead to the formation of large vortices, it is a significant factor in combustion instability.

We have considered in detail the problem of a diffusion flame aligned with and moving along the horizontal axis with a pressure gradient along the axis. Utiliziing the Howarth transformation and a power law for the pressure distribution, the problem may be treated in a manner analogous to the Falkner-Skan treatment of the laminar boundary layer. In this case, however, the equations of energy and of species conservation complicate the problem but require only the simultaneous solution of two nonlinear ordinary differential equations. This work is in progress.

B. Experimental Work

During the fifth year of this program, we have carried out experiments in a facility which has a blowdown air-fuel system and a plenum chamber about 50 cm long and 15 cm in diameter which supplies a combustible gas to a combustion chamber. This chamber is 2.5 by 7.6 cm in cross section and one meter in length. It has windows on the 2.5 cm high sides and pressure and other instrumentation ports on the water cooled 7.6 cm wide walls. Flame holders designed to simulate some of the features of a dump burner are placed 40 to 100 cm from the down stream end of the combustion chamber. The flame holder blocks from 50 to 75% of the duct height.

First, for a range of operating conditions, the flame geometry is unaffected by pressure oscillations in the combustion chamber. A shear layer forms downstream of the flame holder lip, see figure 1a, and the interface between unburnt mixture and the hot burned gas in the recirculation zone behaves like a conventional shear layer. Discrete vortical structures develop in the shear layer and grow by a doubling process. The growth of the width of the shear layer is what we would expect from an adiabatic flow with the same 6:1 density ratio across the layer. Thus, the heat released in the shear layer by the combustion process does not appear to have a large effect on the lateral growth of the shear layer.

Under the conditions described here, a large amplitude, longitudinal pressure oscillation is present in the combustion chamber with a mode shape that has a pressure anti-node just upstream of the flame holder lip and a node near the exit of the chamber. We have not observed any coupling between this oscillation and the flow near the flame holder lip, and the driving mechanism of the disturbance has not yet been studied in detail.

In contrast, at other operating conditions, the geometry of the flame near the flame holder lip is distorted by the presence of large vortices which are shed periodically from the flame holder lip. The shedding frequency is that for a resonant or acoustic mode of the system which produces a large velocity fluctuation at the flame holder lip. The vortices grow rapidly in diameter as they drift downstream and they reach a scale about equal to the duct height and begin to impinge on the wall by the time they have moved three to five duct heights downstream from the flameholder lip. This instability is illustrated in Figure 1b, c, d, and e where the vortex generation and impingement processes are shown. The phase of the pressure signal relative to the maximum in the pressure perturbation is given to the right of each sketch. When the vortex impinges on the wall and the rate of heat addition is increased, see sketch 1e, the phase is greater than 270 degrees. Thus, the heat addition and pressure perturbations are almost in phase in this part of the duct, and consequently the heat addition perturbation will feed energy into the acoustic disturbance. This process has been observed for frequencies between 188 and 530 Hz.

The frequency at which the vortices are shed and frequency of the accompanying acoustic field are equal and are independent of the mean velocity of the combustible mixture or the fuel-air ratio. However, the frequency does depend on the geometry of the system which fixes the acoustic modes, and the instability can be suppressed entirely by suitable addition of acoustic damping to the system. The instability also may be suppressed by suitable choices of velocity and fuel-air ratio.

Thus, the phenomena is clearly not due to either an instability in the shear layer, such as is responsible for vortex shedding in adiabatic systems for which the frequency scales with the velocity, or to the vortices which govern the growth of the unperturbed shear layer discussed above.

Changing fuel mixture ratio affects the range of the fuel-air ratios over which the disturbance can exist. For example, as the hydrogen mass fraction in the fuel increases (and thus as the chemical reaction times decrease), the disturbance occurs for leaner fuel-air ratios, and changes occur in the acoustic mode which is excited.

We have examined the correlation of local values of pressure fluctuation p' and light intensity I'. The latter signal we expect is proportional to the local fluctuation in heat release. When this product P'I' integrated over a cycle is positive, energy is fed into the acoustic mode. A plot of this integral is shown in Figure 2 for one case and for positions throughout the combustion chamber. The integral of this function over the duct is a measure of the rate at which energy is fed into the acoustic mode by the combustion process. The integral for the curve of Figure 2 is slightly positive as it should be because in a steady oscillation the energy fed into the mode only compensates for that lost due to damping. Note that driving occurs (i.e. the signal is positive) for the region near the flame holder where the vortices interact strongly with the flow.

The data we have gathered suggest that the combustion instability process can be described as follows: because of the geometry of the supply section and combustion chamber, one of the resonant acoustic modes of the system will produce a strong velocity fluctuation at the flame holder lip. When this fluctuation is present and is large enough, it causes a vortex to be shed from the lip of the flame holder. This vortex grows as it moves downstream and when it impinges on the wall of the burner, the rate of mixing between hot burnt gas and cooler unburnt mixture is greatly increased by the interaction. After a short time, the chemical reaction time, the unburnt mixture which was heated by this mixing process will burn and produce a large increase in the rate of production of hot products. This nonsteady volume source produces the pressure fluctuation which is required to supply the acoustic energy which maintains the oscillation.

The amplitude of the fluctuation has a self regulating feature because the velocity of the vortex toward the wall and its growth rate appear to depend on the magnitude of the velocity fluctuation. Thus the time required for the vortex to reach the wall and cause the increase in the burning rate will depend on the amplitude of the initial velocity fluctuation which produces the vortex. For a given system, the amplitude grows until the frequency matches some resonance of the system; further growth will decrease the driving force because the phase relationship between the pressure pulse due to unsteady heat addition and the phase of the acoustic signal will be incorrect. Thus, a wide range of frequencies can be driven by this process.

We are continuing to investigate this process to establish unambiguously the relationship between the resonator, the vortex shedding process, and the combustion feedback mechanism. At present, it is clear that the process depends on the gas speed, fuel-air ratio, and the geometry of the supply duct and combustion chamber. In addition, we are also investigating instabilities which depend on the reflection of acoustic energy from a nozzle contraction.

III. Publications

Yang, V. and Culick, F. E. C., "Linear Theory of Pressure - Oscillations in Liquid-Fueled Ramjet Engines," AIAA Paper 83-0574 AIAA 21st Aerospace Sciences Meeting (January, 1983).

Yang, V. and Culick, F. E. C., "Linear Theory of Pressure Oscillations in Liquid Fueled Ramjet Engines," 1983 JANNAF Propulsion Meeting (February, 1983).

Awad, E. and Culick, F. E. C., "Existence and Stability of Limit Cycles for Pressure Oscillations in Combustion Chambers," AIAA Paper 83-0576 AIAA 21st Aerospace Sciences Meeting (January, 1983).

Marble, F. E., "Growth of a Diffusion Flame in the Field of a Vortex," Advances in Aerospace Sciences, 1985.

Karagozian, Ann R., "An Analytical Study of Diffusion Flames in Vortex Structures," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA, 1982.

Norton, Olin P., "The Effects of a Vortex Field on Flames with Finite Reaction Rates," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA, 1983.

Karagozian, Ann R., Marble, Frank E., "An Analytical Study of Diffusion Flames in Vortex Structures," International Combustion Institute, Western States Section, Pasadena, CA.

Yang, V. and Culick, F. E. C., "Numerical Calculations of Pressure Oscillations in a Side-Dump Ramjet Engine," 1984 AIAA Aerospace Sciences Meeting.

Yang, V. and Culick, F. E. C., "Analysis of Unsteady Inviscid Diffuser Flow with a Shock Wave," (to be published, AIAA J. Propulsion and Power).

Yang, V., "Pressure Oscillations in Liquid-Fueled Ramjet Engines," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA, 1984.

Awad, E., "Nonlinear Combustion Instabilities in Combustion Chambers," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA, 1984.

Awad, E., and Culick, F. E. C., "On the Existence and Stability of Limit Cycles for Longitudinal Acoustic Modes in a Combustion Chamber," (to be published in Combustion Science and Technology.

Smith, Duane A., "Vortex Driven Combustion Instabilities Inside Ramjet Type Combustors," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA, June 1985.

Smith, D. A. and Zukoski, E. E., "Combustion Instability Sustained by Unsteady Vortex Combustion," AIAA/SAE/ASME/ASEE 21st Joint Propulsion Conference, July 8-10, 1985, Monterey, CA.

IV. Personnel

Faculty

F. E. C. Culick
F. E. Marble
E. E. Zukoski

Graduate Research Students

G. Hendricks
J. Humphrey
D. Smith
V. Yang
T. Zsak

V. Interactions With Industrial and Government Research Groups

Professor Culick has maintained continuing contacts with two groups at the Naval Weapons Center (Dr. K. Schadow and Dr. William Clark). A summary of their collaboration will appear in a paper accepted for publication in the AIAA Journal of Propulsion and Power. Professor Culick also continues exchange of information with groups at Wright Field, the Johns Hopkins Applied Physics Laboratory and the McDonnell-Douglas Research Laboratory.

Professor Marble has a continuing association with NASA Lewis in the field of non-steady combustion, lean pre-mixed combustion and combustion-related turbine cooling problems. In addition he spends some time each year with the Gas Turbine Laboratory of the Massachusetts Institute of Technology on problems of combustion, turbomachinery instability, and combustion related turbine cooling problems. Professor Marble is a consultant to Northrop Aircraft on propulsion and combustion problems.

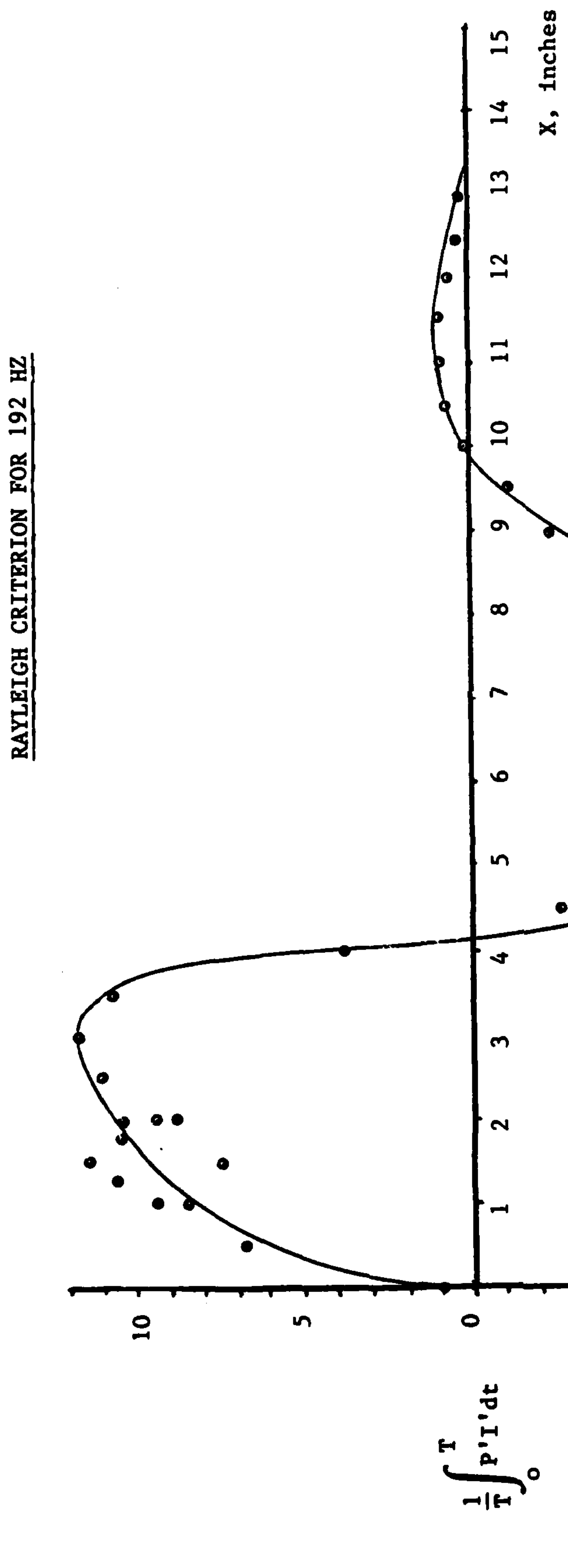
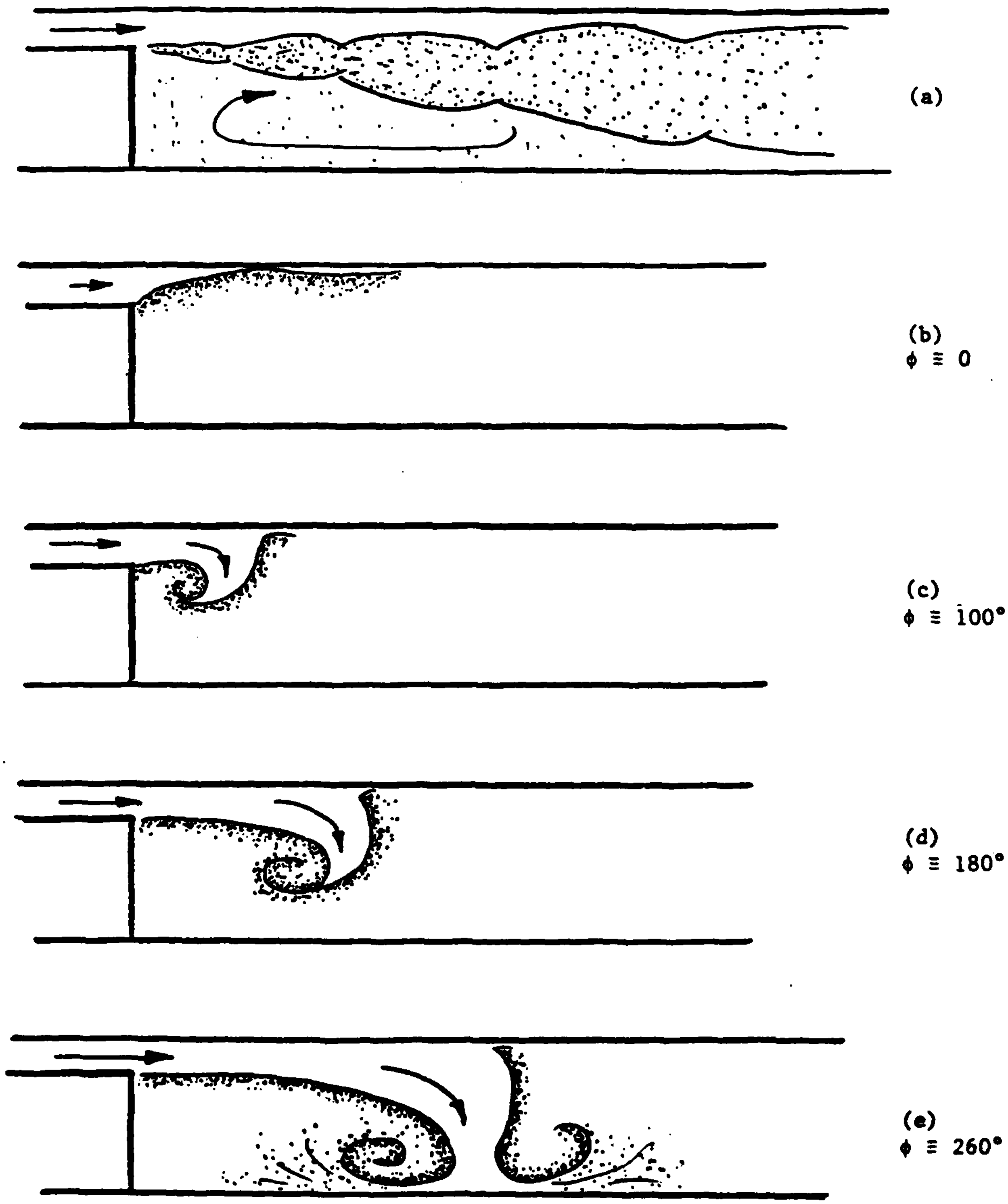


FIGURE 2. Check on Rayleigh Criteria for the 192 hz Case.



(a) Steady Combustion.
(b) to (e) Unsteady Combustion, with vortex shedding.

FIGURE 1. Flame Configuration at Various Phases ϕ with Respect to the Pressure Maximum at $\phi = 0$.

RAYLEIGH CRITERION FOR 192 HZ

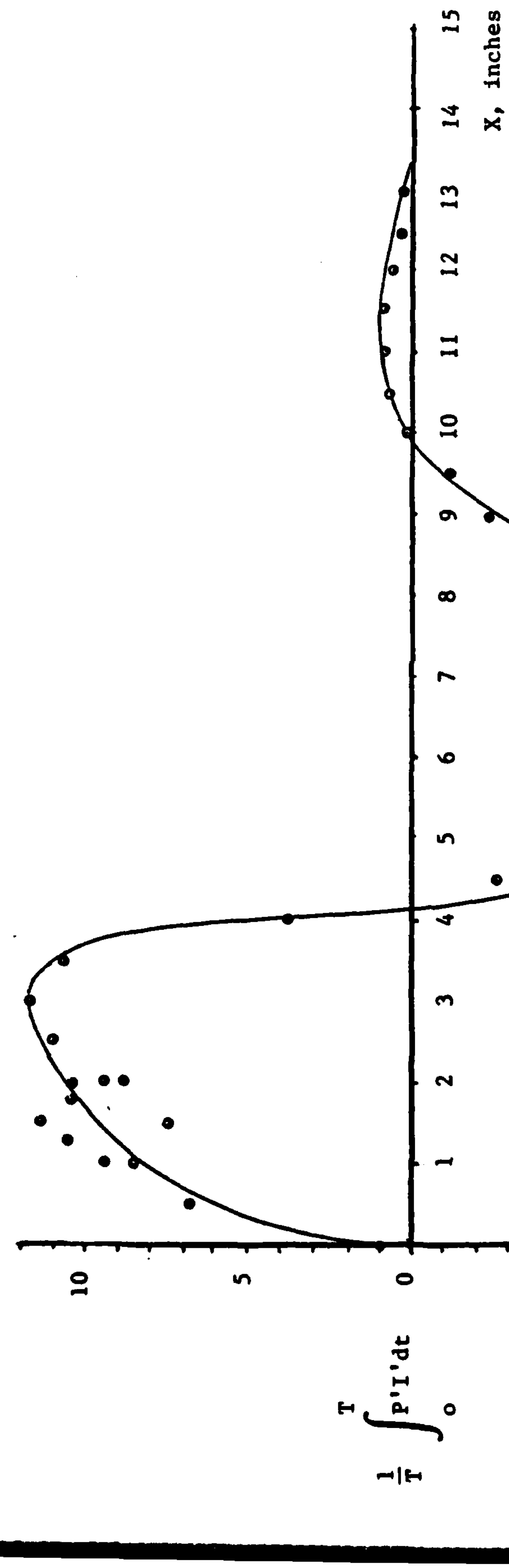


FIGURE 2. Check on Rayleigh Criteria for the 192 hz Case.

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